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Review Article

Static Force Measurement Using Piezoelectric Sensors

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In force measurement applications, a piezoelectric force sensor is one of the most popular sensors due to its advantages of low cost, linear response, and high sensitivity. Piezoelectric sensors effectively convert dynamic forces to electrical signals by the direct piezoelectric effect, but their use has been limited in measuring static forces due to the easily neutralized surface charge. To overcome this shortcoming, several static (either pure static or quasistatic) force sensing techniques using piezoelectric materials have been developed utilizing several unique parameters rather than just the surface charge produced by an applied force. The parameters for static force measurement include the resonance frequency, electrical impedance, decay time constant, and capacitance. In this review, we discuss the detailed mechanism of these piezoelectric-type, static force sensing methods that use more than the direct piezoelectric effect. We also highlight the challenges and potentials of each method for static force sensing applications.

1. Introduction

Force sensation as part of tactile information is an important feedback mechanism to perceive external stimuli in human explorations [1–3]. Force sensing is also necessary to obtain accurate force feedback in robotics and automated medical device applications [4–7]. For these applications, sensors have specific requirements such as small size, lightweight, structural robustness, low cost, and low power consumption [8–11]. In the last few decades, many electromechanical force sensing techniques have been developed to satisfy these requirements, including piezoresistive-, capacitive-, and piezoelectric-type sensors [12–15]. Among these sensing methods, piezoelectric (PE) sensing is one of the most popular methods because it uses a direct piezoelectric effect that can efficiently measure dynamic forces [16–19]. In addition, piezoelectric force sensors offer distinct advantages such as mechanical robustness and noise resistance compared to other types. However, PE force sensors have a major drawback that limits their practical use in static force measurements [20–23]. When a static force is applied to piezoelectric force sensors, the induced electrostatic charge begins to exponentially decrease according to the following equation, $q = Qe^{-t/RC}$ (q is the amount of charge after a certain time, Q is the original value of generated charge, R is the resistance of the feedback resistor, C is the total capacitance of the sensor system, and t is the measurement time). The product of R and C is known as the discharge time constant (DTC) which implies the time required for the induced charge to decrease by 37% of its initial value. For the sufficiently long DTC with adequate signal processing, quasistatic forces can be possibly measured, but there are still limitations in the time window for measuring static forces due to the current leakage [24]. This characteristic makes typical piezoelectric force sensors only suitable for time-varying (dynamic) force measurements despite their advantages over other types of force sensors. Numerous designs of piezoelectric sensors have been suggested for static force sensing using various measurement parameters including the resonance frequency, decay time constant, and capacitance [25–30]. Recent studies also demonstrated that the electrical impedance or admittance amplitude at resonance (or antiresonance) varies by applied force-induced acoustic load variation with feasible sensitivity and linearity which can be effectively used for static force sensing [31–33]. Despite increasing attention for taking full advantage of piezoelectricity in static force sensing, a collective resource that provides a comprehensive review of each measurement mechanism is hardly available to date. Several review articles regarding general piezoelectric force sensors were published, but those articles mainly focused on the direct piezoelectric sensing of dynamic and quasistatic force with very limited information of static measurement [34–37]. In this review, we focus on static force measurement techniques using piezoelectric-type sensors. Most piezoelectric-type yet static force sensors were reported later than 2000 since the motivation usually came from their contrasting performance in static force measurements compared to highly-efficient, well-known piezoelectric sensor designs for dynamic force measurement. Thus, our review covers relatively recent literature (mainly from 2000 to 2020) with the keywords of "piezoelectricity" and "static force sensor".

2. Static Force Measurement Using Piezoelectric Sensors

Several studies have been conducted on static force measurement using piezoelectric sensors. In most cases, piezoelectric resonant-type sensors based on the inverse piezoelectric effect have been used for static measurement applications. The piezoelectric resonant sensor detects the change of the resonance conditions of a piezoelectric material induced by external stimuli [38–46]. This sensor also requires the voltage source to oscillate the resonator at a specific frequency [47–49]. Since this type of sensor is not affected by leakage current, it can be effectively used for both dynamic and static measurements without the signal drift.

Static force can be measured by using the change in the resonance frequency of the piezoelectric sensor [25–27, 31–33]. The resonance frequency is determined by the effective stiffness (or spring constant) and mass of the sensor structure. When a force is applied to the sensor, the sensor structure is deformed and the stiffness changes with respect to the applied force. As a result, the force can be detected by measuring the resonance frequency shift of piezoelectric materials. Meanwhile, the piezoelectric property change including the compliance coefficient and the piezoelectric constant affects both the resonance frequency and the electrical impedance of the sensor. Since these properties are sensitive to the applied force, a static force can be estimated by measuring the frequency and impedance shift according to the piezoelectric property variation. In addition, static forces can be measured by utilizing the resonance frequency or electrical impedance shift due to a change in boundary conditions such as surface acoustic loading and mechanical clamping effects. On the other hand, it is known that the decay time constant of piezoelectric sensors is directly affected by the applied force [28]. Therefore, it is also possible to sense the static force through the measurement of the decay time constant in the piezoelectric sensor system. Finally, the typical piezoelectric material is a dielectric material that can be considered a capacitor [29, 50, 51]. Thus, the capacitive measurement of the piezoelectric sensors can be used for static force sensing. In this section, these mechanisms are discussed with a summary of the reported performances.

2.1. Resonance Frequency Measurement. Gehin et al. have studied a static force sensing method using the piezoelectric resonant sensor based on the resonance frequency measurement [25]. The piezoelectric sensor was made of lead titanate zirconate (PZT), and the structure consisted of a thin circular steel plate clamped between two aluminum rings as shown in Figure 1(a). The prototyped sensor was driven by an alternating voltage, and static forces were applied to the diaphragm by using an aluminum tube fixed on the circular plate. It was observed that the resonance frequency (800 Hz) of the prestressed sensor increased linearly when the applied force increased ranging from 0 to 17.7 N. The sensitivity was found to be 6.6 Hz/N with the hysteresis of 1.76% of the span. The maximum input force was estimated to be 42 N considering the yield stress of the diaphragm material. The relatively high-temperature sensitivity (9 Hz/°C) was also observed due to the different coefficients of thermal expansion and temperature dependence of elastic modulus for the sensor materials.

Barthod et al. have developed a piezoelectric resonant sensor with the structure of double-ended tuning forks (DETF) for force sensing applications [26]. A prototyped sensor consists of a thin circular plate, two beams, a tube, and two piezoelectric elements (PZT) as shown in Figure 1(b). The circular plates and beams were made of Invar alloy whose thermal expansion coefficient was close to that of PZT to minimize the temperature effect. The beams were directly machined into the circular plate by using a chemical machining technique to avoid unequal loading effects. The piezoelectric elements were attached to the top surface of the beams using the conductive paste. An alternating voltage was applied to one of the piezoelectric elements to obtain the second vibrational mode of sensor structures. When the force was applied to the circular plate through the tube, the beams were also stressed, and thus, the resonance frequency increased. The experimental results of the prototyped sensor showed that the resonance frequency increased linearly over the tested force range (10.8 N to 30 N). The sensitivity and hysteresis were found to be 10.5 Hz/N and 1.8%, respectively. It is noteworthy that a much less temperature sensitivity of 0.3 Hz/°C was observed compared to the typical diaphragm design sensor (9 Hz/°C).

Recently, Safour and Bernard have investigated a piezoelectric resonant sensor for high static force (~1500 N) sensing applications [27]. A ring-shaped piezoelectric specimen made of PZT was prepared for the experiments, and a compression machine (Zwick/Roell Z030) was used to compress the specimen as shown in Figure 1(c). The preliminary experimental results showed that the resonance frequency increased nonlinearly with respect to the applied force. Lowered spectrum quality for higher force values (>500 N) was observed due to the parasitic vibration modes on the main spectrum which limited the force measuring range

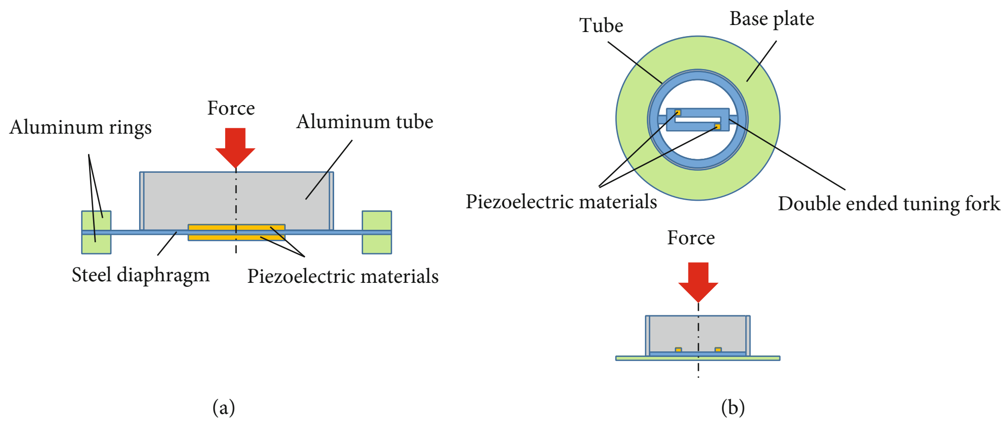

Figure 1: Schematics of piezoelectric sensors for static force measurements using the resonant frequency measurement method: (a) typical diaphragm design, (b) double-ended tuning fork design, and (c) ring-shape design.

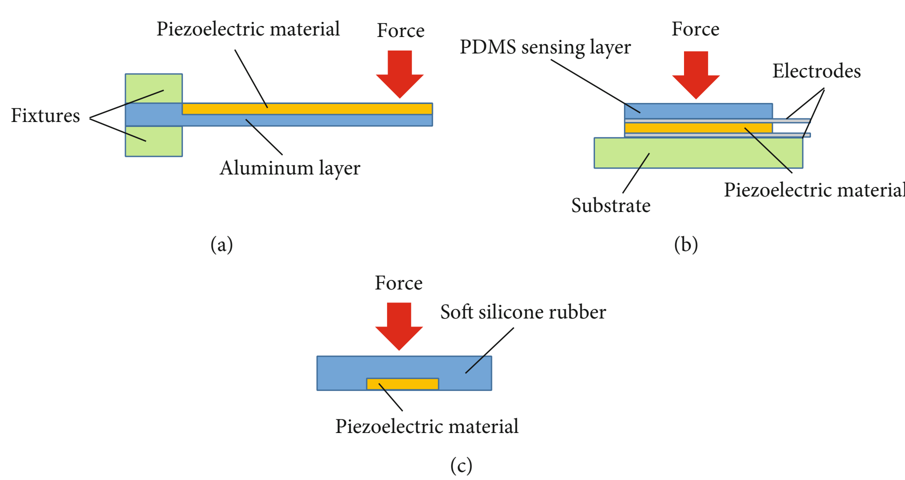

Figure 2: Schematics of piezoelectric force sensors for static force measurements using the electrical impedance measurement method: (a) unimorph cantilever beam design, (b) hyperelastic sensing layer on the resonator design, and (c) embedded resonator design for the smart skin application.

significantly. The unwanted vibration modes were mainly caused by the constrained condition at the contact interfaces. To eliminate this phenomenon, soft material-based layers such as a rubber or Polytetrafluoroethylene (PTFE) were applied to the surface of the piezoelectric material. The experiment results showed the improved sensor performance with the increased linearity and eliminated parasitic mode. The maximum force range and the sensitivity were found to be 1500 N and 1.9 Hz/N, respectively. However, there was also a decrease in the quality factor due to the high mechanical loss of the layer, which means that it is necessary to design an appropriate soft layer according to the required sensing applications.

2.2. Electrical Impedance Measurement. Lin et al. have demonstrated a static force sensing technique through electrical impedance (admittance) measurement of a piezoelectric resonant sensor [31]. A unimorph cantilever beam (UCB) with a PZT layer and an aluminum layer was used for the prototyped sensor to take advantages of simple structures compared to the

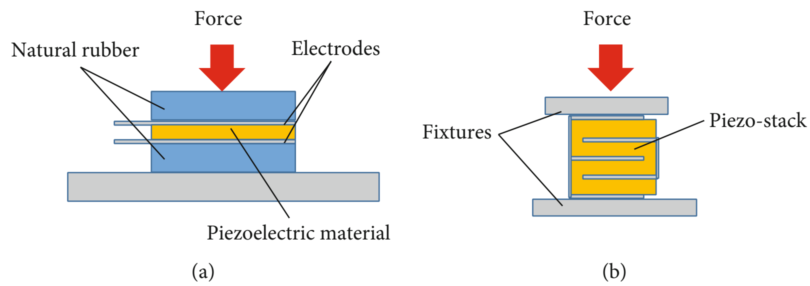

Figure 3: Schematics of static force sensing technique: (a) current decay time measurement using a disk-shaped PZT element and (b) capacitance measurement using a commercial PZT piezostack.

double-ended tuning fork-type sensors as shown in Figure 2(a). The static force was applied to the top of the beam, and compression forces were measured by a load cell. The minimum and maximum force ranges for the experiment were determined to be 0.5 N and 5 N considering the linear response and the yield stress of the cantilever, respectively. Then, the electrical admittance shift at the fixed frequency (3903 Hz) of the resonant sensor was measured, and the applied static force was computed with obtained data. From the experimental results, the full-scale output (FSO) was found to be $10.1 \times 10 - 5$ S for 0.5 to 5 N force range, which was corresponding to the electrical impedance of 9900 ohms and the force sensitivity of 2200 ohms/N. In addition, the nonlinearity was found to be 25.4% FSO and the hysteresis error was 9.2% FSO.

Recently, Kim et al. have studied a static force measurement technique using a specially designed piezoelectric resonator and sensing layers [32]. In this study, a face-shear mode lead magnesium niobate-lead titanate (PMN-PT) single-crystal resonator was adopted for the sensing element to take an advantage of its high sensitivity to the acoustic load [52]. Also, the concept of a hyperelastic sensing layer was first introduced and applied for converting the applied static force into the acoustic load impedance. When the force is applied to the sensing layer, the elasticity of the layer changes due to the characteristic of the cross-linking system of hyperelastic materials [53, 54]. As a result, the acoustic impedance of the sensing layer also increases since the acoustic impedance is determined by the values of its elasticity and density [55, 56]. The change in acoustic load impedance due to the change in elasticity can be measured with high sensitivity using the acoustic load sensing technique with face-shear mode piezoelectric resonators [52, 57]. The acoustic load impedance is directly related to the electrical impedance of the sensor, and thus, the static force can be simply sensed by measurement of the resonator's electrical impedance. The schematic of the prototyped sensor is shown in Figure 2(b). For the force sensing test, normal forces ranging from 0.1 to 2.0 N were applied to the prototyped sensor and the electrical impedance shift of the sensor was measured through the top and bottom electrodes. It was observed that the electrical impedance increased linearly as applied normal forces increased. The sensitivity and accuracy of the sensor were found to be 51 ohms/N and 50 mN (±2.5%) in the range of 0.1-2 N from an ideal transfer function, respectively.

Liu et al. have developed a static force sensing technique using an electromechanical impedance measurement with the piezoelectric resonator for smart skin applications [33]. A prototyped sensor was made of a PZT plate with a resonance frequency of 900 kHz and embedded in the skin-like soft silicon rubber material as shown in Figure 2(c). Calibration weights (0.5 N–2.5 N) were used for applying static forces, and the impedance signal was recorded using an impedance analyzer with frequency ranges of 100 kHz to 3 MHz. The tactile index (TI) was used as a diagnostic method that compared the average impedance values to reduce the noise effects. As a result of the experiment, it was observed that the TI value consistently increased as the static force increased, and the sensitivity was found to be about 1.8%/N with the resolution of 0.5 N. In this study, a detailed numerical simulation was also successfully performed to model the electromechanical impedance response of piezoelectric sensors.

2.3. Decay Time Measurement. Ozeri and Shmilovitz have developed a static force sensing technique based on the decay time constant measurement of the piezoelectric sensor [28]. A disk-shaped PZT element with a resonance frequency of 70 kHz was prepared, and natural rubbers were attached to the top and bottom of the element as described in Figure 3(a). For experiments, the static forces (from 14.1 N to 141.3 N) are applied to the sensor and excited with a sinusoidal voltage signal (exciting phase). At the end of the excitation phase, the series RLC current begins to exponentially decrease (free oscillating phase). Then, the change in current during a specific time is measured, and the decay time constant is calculated with measured values. Since the decay time constant directly reflects the amount of change in the force applied to the sensor, it can be effectively used for static force measurement. From the experiments, it was revealed that the decay time decreased as the applied static force increased nonlinearly. In this method, the circuit system constituting the sensor can be simplified because it uses the amount of change in the current for a certain period for the measurement rather than the current that occurred at a certain moment.

2.4. Capacitance Measurement. Sekalski et al. have investigated static force sensing using capacitance measurement with a stacked piezoelectric resonator [29, 50]. A commercial PZT piezostack (Physik Instrument) was used for force sensing experiments, and the normal forces ranging from 730 N to 4 kN were applied to the PZT stack as shown in

Table 1: Comparisons of different types of piezoelectric static force sensing methods.

Measurement type	Material	Sensor structure	Sensitivity	Sensing range	Output central value	Linearity error	Hysteresis	Thermal drift	Repeatability	Ref.
Resonant frequency measurement	PZT (CeramTec)	Diaphragm	6.6 Hz/N	0-17.7 N	890 Hz	3.5%	1.76%	9 Hz/C	0.7%	[25]
	PZT	Double-ended tuning forks	10.5 Hz/N	10.8-30 N	2500 Hz	3.6%	1.80%	0.3 Hz/C	2%	[26]
	PZT (Noliac)	Ring shape	1.9 Hz/N	50-1500 N	172 kHz	6.7%	—	—	—	[27]
Electrical impedance measurement	PZT	Unimorph cantilever beam	2200 ohms/N	0.5-5 N	3900 ohms	25.4%	9.20%	—	15.1%	[31]
	PMN-PT	Embedded in the polymer	51 ohms/N	0.1-2 N	318.5 ohms	4.3%	—	—	—	[32]
	PZT (APC ceramics)	Embedded in the polymer	1.8%/N	0.5-2.5 N	2700 ohms	11.2%	—	—	—	[33]
Current decay time measurement	PZT	Disk shape	1 μsec/N	14.1-141.3 N	186.5 μsec	11.9%	—	—	—	[28]
Dielectric capacitance measurement	PZT (PICMA)	Piezostack	25 nF/kN	0.7-4 kN	3170 nF	3.6%	10%	—	—	[29]

Figure 3(b). It was observed that the capacitance increased as a function of the loaded force with the sensitivity of 25 nF/kN and the repeatability of ±5%. When a relatively large force (>500 N) was applied, the capacitance increased linearly, whereas, in the case of a small force loading (<100 N), it showed nonlinear behavior. This is believed to be due to the large elastic modulus of the piezostack, which makes it difficult to change the capacitance with small force loading. The capacitance measurement method using the piezostack showed potential for the large static force sensing applications due to its linearity and wide measuring range.

3. Conclusion and Future Work

The piezoelectric force sensor is widely used for measuring dynamic and quasistatic forces due to its distinct advantages over other types of sensors. For static force sensing, various types of piezoelectric sensing technique have been researched including resonance frequency, electrical impedance, current decay time, and dielectric capacitance measurements. The main features of these types of sensors are summarized in Table 1. The frequency measurement method which is most widely researched shows excellent linearity compared to other methods. On the other hand, the electrical impedance measurement method is one of the most promising techniques and is suitable especially for small force measurements because it presents a high sensitivity to small forces. However, both the frequency measurement and electrical impedance measurement methods suffer from a large temperature effect since resonance frequency and electrical impedance are strongly affected by the environmental temperatures. This influence on the temperature can be minimized by using proper piezoelectric material that is relatively insensitive to temperature changes [58–62]. In addition, the temperature effect can be reduced when the sensor structure is designed in consideration of the coefficient of temperature for all sensor components [63, 64]. Meanwhile, it was revealed that the sensitivity of the electrical impedance measurement varies depending on the vibration mode of piezoelectric material [52, 57]. Thus, for piezoelectric force sensors utilizing the electrical impedance method, it is necessary to determine the optimized vibration mode of piezoelectric sensing materials. The decay time measurement method has the advantage of broad operating frequency and simple and low-cost circuit, but further research will be needed for practical applications. In the case of the capacitance measurement method, it is suitable for large force measurement, but it can be inappropriate for small force measurement due to the high stiffness of piezoelectric materials. To obtain a high sensitivity to the small force, piezoelectric polymers with low stiffness such as polyvinylidene fluoride (PVDF) can be considered sensing materials [65–67]. Alternatively, a dielectric polymer layer or a cavity structure can be added to the sensing layer to increase the total capacitance change [68, 69]. Finally, a dual-mode piezoelectric sensor design can be potentially used by combining multiple operation modes. By analyzing the variations of more than two different parameters by force variations, the higher sensitivity and higher repeatability are possibly expected for force sensing applications. We expect that the summary in this review can be a foundation for designing highly sensitive, low-cost, piezoelectric static force sensors.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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